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Mapping of water frost and ice at low latitudes on Mars

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ABSTRACT

This paper reports on mapping of water frost and ice on Mars, in the range of latitudes between 30°S and 30°N. The study has been carried out by analysing 2485 orbits acquired during almost one martian year by the Mars Express/OMEGA imaging spectrometer. Water frost/ice is identified by the presence of ∼1.5 μm, ∼2 μm and ∼3.0 μm absorptions. Although the orbits analysed in this study cover all seasons, water frost/ice is observed only near the aphelion seasons, at Ls = 19° and at Ls = 98–150°. Water frost/ice is detected mainly on the southern hemisphere between 15°S and 30°S latitude while it has not been identified within 15°S–15°N. In the northern hemisphere, the water frost/ice detection is complicated by the presence of clouds. Usually, water frost/ice is found in shadowed areas, while in few cases it is exposed to the sunlight. This indicates a clear relationship with the local illumination conditions on the slopes which favour the water frost/ice deposition on the surface when the temperatures are very low. OMEGA observations span from 10 to 17 LT and the frost/ice is detected mainly between 15 and 16 LT, with practically no detection before 13 LT. We think this is due to the fact that the 10–12 LT observations occur at large distances and it is not a local time effect. A thermal model is used to determine the deposition conditions on the sloped surfaces where water frost/ice has been found. There, daily atmospheric saturation does not occur on pole facing 10–25° slopes with current water vapour abundances but only by assuming values greater than 40 pr μm. Moreover, the water frost/ice is not detected during the northern winter, even if the thermal model foresees daily saturation on 25° slopes.

1. Introduction

Water vapour is one of the minor constituents of the martian atmosphere still playing a key role in the planet's climate, together with the carbon dioxide and the dust (e.g. Smith, 2002). Under the current martian climatic conditions, H_2O can only exist in a solid or gas phase, since the general conditions of pressure and temperature do not permit the existence of the liquid phase, although it could exist in few regions (Haberle et al., 2001). The key factors for the deposition of water frost/ice on the surface are the temperature and the relative humidity in the atmosphere, the more it increases, the higher the possibility that water vapour condenses onto the surface. On Mars, assuming an average partial pressure of water vapour of 0.06 Pa on the surface, the frost point temperature is ∼193 K; this value changes with the local conditions which have a geographic dependence, but in the southern hemisphere the frost point temperature does not exceed 196 K (Farmer and Doms, 1979; Schorghofer and Edgett, 2006). In other regions where the partial pressure is lower, the values do not vary too much. For example, at 0.01 Pa the water vapour saturates at ∼183 K (Schorghofer and Edgett, 2006).

Several clues for the presence of water ice on Mars, in the atmosphere, on the surface and in the sub-surface have been reported. It is known that water ice is present in the North and South Polar Cap deposits (e.g. Titus et al., 2003; Bibring et al., 2004a; Langevin et al., 2005), inside clouds in the form of water ice crystals (e.g. Curran et al., 1973), at high latitudes in the form of frost and ice (e.g. Jones et al., 1979; Wall, 1981; Svitek and Murray, 1990), and recently at the Opportunity rover landing sites (Landis, 2007).

The identification of the regions on Mars where ice can be stable has been the main goal of several scientific works. Early theoretical modelling suggested that ground ice is stable only at high latitudes (Leighton and Murray, 1966). The authors proposed that water vapour can penetrate into the soil to a depth of few meters and condensate in the regions poleward of latitudes 40–50°, but they do not exclude that ice that can be present in equatorial regions. Farmer and Doms (1979) came also to a similar conclusion by using the Viking observations of the seasonal variation of the distribution of water vapour. Their results are consistent with a permanent reservoir of ice buried at a depth of 10 cm to 1 m at latitudes poleward of 40°. Clifford and Hillel (1983), on the basis of the physical properties of the martian regolith, concluded that the necessary conditions for a long-term survival of ground ice may exist in isolated regions within the equatorial regolith. In following works surface thermal properties have been also consid-

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ered. For example, Mellon and Jakosky (1993, 1995) investigated the stability of ground ice with thermal and diffusive models of the martian regolith and they produced the first map showing the ice at global level. Apart some regions in the northern hemisphere where the boundary of ice stability is near 30° latitude, in general it falls at about 45–50° range on both hemispheres, confirming results of previous studies. Indirect measurements of the surface/subsurface ice distribution have been carried out by the GRS instrument, on board the Mars Odyssey 2001 (Feldman et al., 2002; Boynton et al., 2002). These measurements have pointed out abundant reservoirs of hydrogen (interpreted as an indication of water) in a superficial layer of 1 m (the depth to which this technique is sensitive) on planetary scale, with a general trend which continually increases from the equator to the poles. From these data it has been estimated a water reservoir residing at low and mid latitudes with mass water abundance between 2% and 10% (Feldman et al., 2005).

Although the observations were not spectroscopic, Schorghofer and Edgett (2006) have documented the occurrence of likely patch water frost al low mid-latitudes and even 24°S. Their thermal model (see also Aharonson and Schorghofer, 2006) has shown that surface ice can be stable to latitudes of about 25° when the effects of topographic slopes are included.

In fact, as we will show in Section 3, slopes play an important role in the formation and stability of frost/ice on the surface. A tentative detection of water frost at low latitude has been also reported by Bellucci et al. (2007).

The water ice at low latitudes could be an important target for future exploration missions searching for habitats suitable for harbouring life (e.g. ESA/ExoMars), or for resources utilization in view of human colonization of the red planet.

This paper reports on the spectroscopic identification and mapping of water frost and surface ice at low latitudes on Mars. The study, carried out with the OMEGA (Observatoire pour la Minéralogie, l'Eau, les Glaces et l'Activité, Bibring et al., 2004b) instrument on board the Mars Express orbiter, covers the range of latitudes between 30°S and 30°N and it includes the analysis of 2485 data cubes. The data acquisition occurred during all seasons, but water frost/ice has been identified during the winter and fall of the southern hemisphere, between ~30°S and ~15°S, and during the summer of northern hemisphere, between ~15°N and ~30°N. Water frost/ice has been detected by the simultaneous occurrence of three absorption bands in the 1.0–2.5 μm spectral range. They are the overtone of the O–H stretches which occur at ~1.5 μm, the combinations of the H–O–H bend with the O–H stretches at ~2.0 μm, and the spectral slope between 2.2 and 2.5 μm which is the wing of the 3 μm absorption (stretches of O–H).

The correlation with the geomorphology, the absence of the Fresnel reflectance peak at 3.1 μm and radiative modelling of atmospheric effects, suggest that H_2O is present as frost or ice on the surface and not in the clouds.

In Section 2 we describe the data set used in this study and the methodology applied for the identification of the water frost/ice on the surface. In Section 3 we report the spatial distribution of frost/ice on both hemispheres and we compare the results with the predictions done by thermal modelling. The results are summarized in Section 4.

2. Data set and analysis procedures

The OMEGA instrument has been designed for mineralogical and atmospheric investigation of Mars. It is an imaging spectrometer covering the 0.35–5.1 μm (visible and near infrared) wavelength range with the instantaneous field of view (IFOV) of 1.2 mrad. This instrument, in order to cover this spectral range, uses three spectral channels: VNIR (0.35–1.05 μm), IR C channel (0.92–2.7 μm), IR L channel (2.7–5.1 μm). In this study we make use of the IR C channel data for frost/ice detection. VNIR images at 0.4 μm have been also used for clouds identification. The study is limited to the range of latitudes from 30°S to 30°N and we have analysed 2485 orbits, acquired from January 2004 until September 2005. The range of latitudes has been divided in four regions: 30–15°S, 15–0°S, 0–15°N, 15–30°N. The distribution of the orbits with seasons is shown in Table 1. Several million spectra are used in this analysis.

Although the strongest water ice bands are centred at ~1.5, ~2.0 and ~3.0 μm, we have limited our analysis only to the IR C channel. This in order to simplify the data analysis of this huge data set, because the C and L channels are not co-registered. The L channel is used only to discriminate between surface and atmospheric ice.

To quantify the water frost/ice absorption features, we have calculated the band depth at 1.5 and 2.0 μm. They are computed by using the following formula:

$$B_d = 1 - \frac{R_a}{R_c}$$

where R_a is the radiance factor (Hapke, 1993) at the absorption of interest λ_a and R_c is the continuum computed at λ_a. Each R_c was evaluated by linear interpolation of two continuum level for each absorption (1.41–1.81 μm, 1.83–2.25 μm) taken outside the atmospheric bands. Moreover, the 2.25/2.43 μm spectral ratio has been taken as a measure of the 3.0 μm absorption strength. Then, we have used the spectral range between 3.0 and 4.0 μm to discriminate between icy clouds and water frost/ice on the surface. Since the CO_2 atmospheric absorption at ~2 μm interferes with one of the water ice absorptions, a first order atmospheric correction has been applied following the method described in Langevin et al. (2005), i.e. each spectrum has been divided by a ratio of spectra of homogeneous terrains from the bottom and the top of Olympus Mons collected by OMEGA and scaled to the same CO_2 column density. Moreover, an estimation of the surface temperature has been derived by measuring the radiance at 5.0 μm, as discussed in Section 3.

As already mentioned before, the identification of water frost/ice has been done by the simultaneous occurrence of three absorptions, the detection levels being: $BD_{\lambda=1.5\mu m} \geqslant 0.02$, $BD_{\lambda=2.0\mu m} \geqslant 0.02$, 2.25/2.43 μm ratio $\geqslant 0.026$. These limits have been determined on the basis of an empirical analysis of a large amount of spectra. Once water frost/ice is identified, we have used the 0.4 μm image to verify that water ice clouds are not present. Then, as a first approximation we consider the 1.5 μm band depth as a measure of water frost/ice amount in the observed footprint. We have used two lower limits for the 1.5 μm band depth: 0.02 and 0.04. The former is fixed at the confidence level of the linearity regime of OMEGA at such wavelength. The latter has been taken as a conservative identification of the water frost/ice spectra. Although the spectra with $0.02 \leqslant BD_{\lambda=1.5\mu m} < 0.04$ show a big spectral variability of the band shape, they are usually located around pixels with deeper band depths and the spatial distribution correlates with geomorphological units such as crater rims, scarps and feet of hills. As it will be shown later, by applying the 0.04 lower limit,

Table 1
Number of cubes object of the study for each season and latitude range.

	Summer	Spring	Fall	Winter
15–30°N	315	126	89	69
0–15°N	321	148	94	60
15–0°S	46	155	137	291
30–15°S	77	139	126	292